System Dynamics Modelling of Photovoltaic Power Generation Investment Decisions

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Abstract. Most countries aim at the generation of electric power through renewable sources. The most developed countries have made great investments pursuing this goal. Photovoltaic energy is one of the options available even to domestic users. However, costs, radiation conditions and average household energy consumption won`t make it a good option everywhere. In this article a model based on system dynamics is proposed, studying the viability of the use of photovoltaic systems at home. In the article, the Colombian case is reviewed 90% of the energy in Colombia is generated through hydroelectric plants and due to its high climate dependence, in times of drought the country is forced to import energy. We figured the number of photovoltaic systems necessary to avoid this importation and calculated the investment required by Colombian households to fulfill their energy needs.

Keywords: Electric power, Solar Panels, Renewable Energy, Demand, Imports, Consumption.

1 Introduction

The demand for energy increases to support the growth of economies, per capita income and in general, the needs of the population, becoming a resource of great importance and therefore a concern for many countries. It is projected that the total energy consumption in the world will grow from 549 trillion BTUs in 2012 to 815 trillion BTUs in 2040, which represents an increase of 48% (U.S. Energy Information Administration (EIA), 2016).

This is an interesting occurrence in terms of global demand, since most of the growth of the world's energy consumption will occur in countries that are not part of the Organization for Economic Cooperation and Development (OECD). An increase of 71% is expected between 2012 and 2040, compared to an 18% increase for the OECD member countries. Between 2007 and 2012, non-OECD countries accounted for 57% of total

energy consumption in the world, but by 2040, almost two-thirds of the world's primary energy will be consumed in economies that are not members of the OECD (US Energy Information Administration (EIA), 2016). Energy consumption is usually proportional to economic growth.

The richer the country the higher the energy demand [1]. All around the world, the events in the energy sector are placing more and more emphasis on renewable energies, because it is possible to reduce not only the impacts of climate change, but also the use of dispensable fossil fuels. More importance is being given to development strategies and the application of the principles of environmental transformation [2].

Currently, one of the renewable energy alternatives is solar photovoltaic systems, where solar radiation is captured in photovoltaic cells to generate electricity. This is achieved by panels with cells containing silicon (a semiconductor that is easily excited by light) thus producing a direct current which is then transferred to a bank of batteries where it is stored and derived to the inverter and finally transformed into alternating current (12 volts) [3].

The feasibility of implementing photovoltaic systems in Bogotá, Colombia will be determined through system dynamics, given that the solar generation capacity increased 26% in 2015, especially due to a reduction in the cost of production and the photovoltaic revolution that is taken place in Latin America, led by countries such as Chile 2015 where more than 362 MW and 873 MW are under construction and planning.

Green Tech Media (GMT), points out that Latin America was the region that showed the highest growth in solar energy in 2014, generating 625 MW, which is equivalent to a growth of 370% in relation to the previous year [4].

The cost of production of solar energy has become cheaper, approaching the costs of gas and coal. The primal factor in the reduction of the costs of production is mainly the decrease in the cost of solar panels, which, according to the International Renewable Energy Agency (IRENA), has been reduced by 80% since 2010 and it is expected to continue decreasing until it becomes one of the cheapest choices by 2040. Also, an important factor, are the new policies, implemented by the International Energy Agency (IEA).

2 Power Generation Analysis and power generation in Colombia

In Colombia, one of the main problems in the implementation solar technology is the frequent changes in climate. The average daily multiannual radiation is only 4.5 KWh / m2. La Guajira could be the best area for this solar resource with a radiation close to 6 KWh / m2 [5]. In [6], the development of solar energy in Colombia until 2008 is presented, emphasizing the need to formulate a program of development based on FENR (New and Renewable Sources of Energy). This program must integrate three essential elements: policy, capacity for development and project development. Only a coherent program can ensure the expansion of the FENR in the country and the use of its resources.

The difficulty in taking conventional electric power to geographically distant sectors, has encouraged the installation of photovoltaic panels, in some rural areas of regions

such as Cundinamarca [5]. Of the 78,000 solar panels installed in Colombia, which produce around 6 MW, 57% are used in rural areas, and 43% for communication towers and traffic signage. It also highlights the importance that Silicon production has both in the execution of the projects and especially in the costs of the facilities. This production is instrumental in the development of photovoltaic solar energy. The capacity of production of silicon for photovoltaic panels would provide greater control and autonomy in the sector [7].

On the other hand, other variables have been taken into account in order to model the power sector using system dynamics. An approach has been used to model changes in energy intensity in the residential sector in Iran using simulation. They are trying to introduce some policies to make a constant improvement of energy intensity in the future [8]. Additionally, the city of Santa Fe, Argentina, is analyzed by system dynamics models that highlight the behavior of energy efficiency, which is directly affected by the production of renewable energy and state policies. An increase in energy efficiency will produce a drop in consumption and price, and together with the use of renewable energy they will make the energy model sustainable [9].

In general, a causal diagram is show in figure 1, using aggregated variables and their relationship, in order to be used as a base to model the dynamics of electrical power consumption.

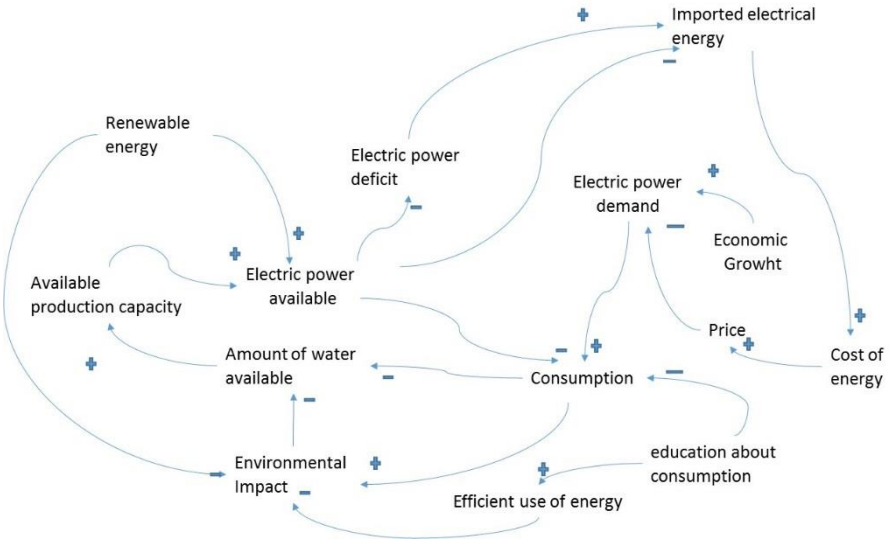

Fig 1. Causal Diagram of Electrical Power Consumption. **Source:** The authors

The situation of the energy sector in Colombia is not the best, due to the crisis at the end of 2015 and in the first months of 2016, caused mainly by the decrease in the capacity of electric supply caused by El Niño, combined with the lack of forecasts by the Colombian government.

El Niño caused droughts throughout the country affecting the levels of hydroelectric dams, thus decreasing their production capacity. The power plants that produce electricity using gas, thermoelectric power plants, were forced to compensate for the increased demand. All this caused a deficit in the production of energy in the country.

On the supply side, the most serious problems are related to: i) lack of incentives to substitute energy from the interconnected system for alternative energies (including sugarcane bagasse or the incorporation of wind power, despite Law 1715 of 2014); and ii) lack of vigilance-control in the use of resources from the "Reliability Charge" paid to thermoelectric power plants [10].

This is how the increasingly depleted reserves of traditional sources of energy, such as fossil fuels, have revealed the need for alternative solutions to energy production, taking value from sources of energy that are more environmentally friendly, in such a way that they reduce the environmental impact [11].

Although the Colombian State Law 1715 of 2014 promotes the use of renewable resources, alternatives of high quality and efficiency that support the energy demand, it is important to consider the great benefits of further diversifying energy production, keeping in mind the great potential of both the country and the region, both for environmental and economic reasons. In certain cases, not only pollution could be reduced, but also periods of price increase would be less frequent [11] Reducing costs and decreasing energy imports could also result.

It is interesting to analyze the economic viability of roof mounted photovoltaic systems in urban areas, comparing their total investment cost with the cost of the energy that is currently being imported and the government subsidies to the different economic strata.

2.1 Photovoltaic systems

The efficiency of conversion of solar radiation into electrical energy is the most critical point for the photovoltaic industry, being an aspect of competitiveness, since, by increasing the efficiency per unit area, the same amount of kWh is generated in a smaller area. In addition, performance depends, among many other factors, on the ambient temperature and the wind speed.Table 1 shows the efficiency of commercially available modules.

Table 1. Efficiency of commercially available modules. NREL. 2010, Solar Technologies Market Report

Technology	Efficiency
monocrystalline silicon	14%
silicio multiocristalino	14%
CdTe	11%
amorphous silicon	6%
CIGS	11%

Inverter. The inverter is the element that interconnects the electricity production of the solar panels with the electrical system (distribution network or island with the network). In addition, the inverter must regulate the current and voltage for the system to work at the maximum power point.

Maintenance. Normal maintenance consists of cleaning the glass panels from time to time. You can learn how to keep the batteries (dry or gel) and monitor the good condition of the system. Most equipment, such as regulators or inverters, have status or performance indicators [16].

Total cost. For international systems, the total costs of a photovoltaic system in June 2011 ranged between US $ 3,300 / kWp and US $ 5,800 / kWp for ceiling mounting systems. In Colombia, the cost is 16.5 USD / Wp on average. That is, up to three times more than what it costs internationally [17].

In the proposed model, we consider the behavior of the costs of the panels in other countries (see Graph 2), taken into account the average annual reduction of 7.7% (during the years 2010 to 2014 31% reduction).

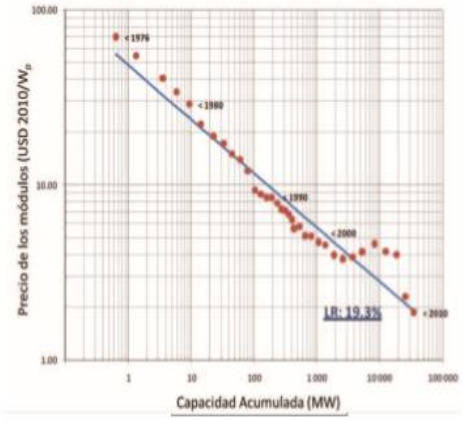

Fig. 2. Drop in costs for PV modules (1976 -2010). International Energy Agency.

3 Data

Electric power generation in Colombia was 55,965.6 GWh in 2009, 2.9% higher than in 2008 (54,395 GWh). This positive evolution can be explained by the increase in demand and exportation of electricity to Ecuador and Venezuela; hydraulic generation decreased 11% because of El Niño and in 2014 the variation compared to 2013 was only 0.8% (see table 2) [12] [13].

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Table 2. Energy Power generated in Colombia 2008 – 2015.

Year	Generated Power (GWH)
2008	54395
2009	55965
2010	56897
2011	58616
2012	59990
2013	62197
2014	64327
2015	66548

As part of the prospective modeling, the UPME (Unidad de Planeación Minero energética) found that between 4,208 and 6,675 megawatts of expansion are required for the next decade, highlighting Scenario 12 with a total of 4900 MW and with the greatest resilience, understood as the ability to adapt to events of hydrological extremes, good behavior in terms of low generation costs, lower capital requirements and one of the lowest greenhouse gas emission [14]. On the other hand, the projection demand for electric power was based on the data of the Ministerio de Minas y Energia of Colombia, who has projected for a high, medium and low scenario for the next 15 years.

The total energy imported since 2003 amounts to 361 GWh corresponding to exchanges with Ecuador and Venezuela at a total cost of USD 18,713.3 thousand [13], as shows Table 3.

Table 3. Imported power in Colombia 2007 – 2015.

Year	Imported power (GWH)	Power cost
2007	38.4	1336
2008	37.5	2309.4
2009	20.8	1118.3
2012	6.5	243.2
2013	28.5	1682.5
2014	46.9	2935.7
2015	45.2	4658.9

The Congress of the Republic, through different laws, in particular the Tax Reforms and the last two Development Plans, has been modifying the validity and use of the sources of government funds created with specific destination for the normalization of networks (PRONE), energization of Interconnected Rural Areas (FAER) and non-Interconnected (FAZNI) and coverage of the consumption of users located in special zones (FOES) [15].

According to the above, and to determine the average annual investment value by the Government, the money destined for the FOES (subsidies) and the Solidarity Fund

for Subsidies and Redistribution of Income (FSSRI) was taken into account, as well as the items that will apply from the budget of the Ministry of Mines and Energy - 2016.

4 Proposed model

A system dynamic model was developed using IThink tool to simulate the power sector in Colombia on a planning horizon of 14 years (see figure 2). Given the average consumption of 1,700 kWh per year of energy per home, it was identified that panels of 2KW are needed, given that in Colombia they can generate from 2500 to 3000 KWh per year depending on the geographical location where they are installed. [18].

Taking into account the annual variability, it is known that this is not inherent in the random behavior of the incidence of solar radiation in many regions of the world. For this reason, it is a general feature that is not specific of a geographic area or a given climate regime [19]. It does not exceed 11%.

To determine the amount of photovoltaic systems needed to supply the amount of energy imported into the country, a trial and error test was carried out, resulting in a total of 11'226.892 units which is equivalent to 1'403.361 panels approximately, taking into account that its useful life is 25 years and the companies that produce these systems guarantee its operation for a period of 10 years. The cost per system amounts to US $ 5639 according to quotes made with domestic suppliers.

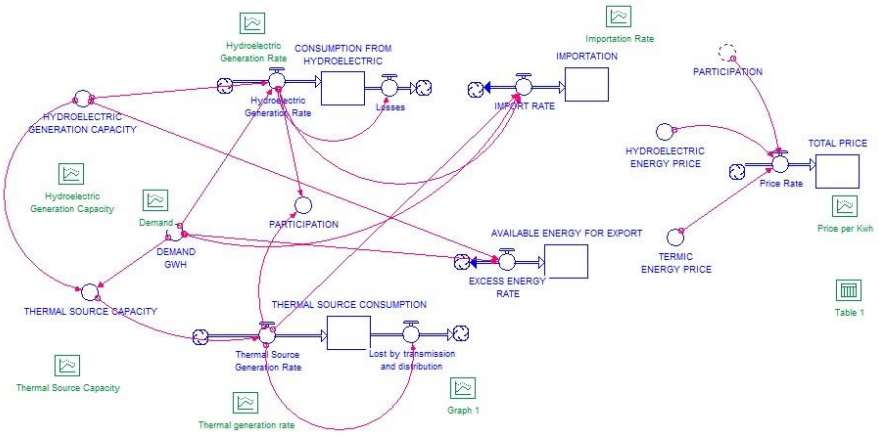


Fig. 3. System dynamic model of Electrical Power Consumption in Colombia.

5 Estimated Results

The total power generated through photovoltaic systems exceeds the amount of energy imported after 11 years, as shows in Fig. 3.

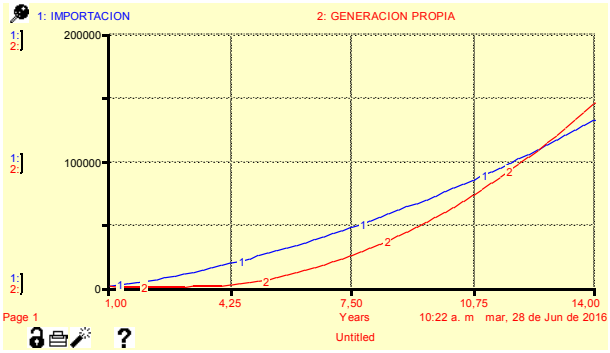
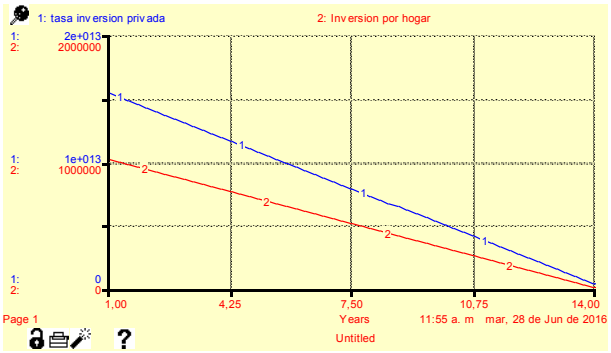


Fig 3. Imported energy behavior vs energy generated through photovoltaic systems

The total investment required for the proposed photovoltaic system amounts to US $ 27,429,454,521.68 with an average annual investment rate of US $ 3,064,984,633.35 and an investment return of US $ 712.6, corresponding to the average cost of current electricity consumption. If the investment of the government funds is taken into account, it is concluded that the highest investment per household is US $ 350.71, and its behavior over time decreases (Graph.4.) given the reduction in the price of the panels.



Graph 4. Investment behavior needed to implement photovoltaic systems vs. investment per household

6 Conclusions

In this paper, we evaluate the technical and economic feasibility of the massive use of solar panels in Colombia using the theory of system dynamics and researching on photovoltaic power generation. We identify the main variables that affect solar energy generation and the impact of investment performance on power generation.

With the total investment projected by the state (78428851 USD) and by the private sector (41103214 USD) (based on information from the Ministry of Mines and Energy MinMinas) in 10 years the photovoltaic generation would have a participation of 9, 82% of the country's total energy generation.

With the subsidies projected by the State (78428851 USD) it would be possible to surpass the import after 11 years, and the electric system would not depend on imported energy. Without such state investment the system would continue to depend on importation.

Without the implementation of solar panels, an average of 386.44GWh-year would be imported in seasons of extreme drought, while when using panels there is a 39.14% observed reduction in imports during the first 10 years.

Without solar panels an average of 111738 USD per year would be imported during the first 10 years.

Although the price of solar panels decreases over the years, it remains a very expensive and uncompetitive alternative, as the country is not willing to invest in this sector. However, an even more detailed study by region, (where the type of system is more specifically established according to solar radiation conditions) should be conducted. As costs decrease there will be more incentives to implement interconnected photovoltaic systems.

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